

CERTS MICROGRID LABORATORY TEST BED

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Prepared By:
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CERTS
CONSORTIUM FOR ELECTRIC RELIABILITY TECHNOLOGY SOLUTIONS



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PIER FINAL PROJECT REPORT

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Preface

The Public Interest Energy Research (PIER) Program supports public interest energy research and development that will help improve the quality of life in California by bringing environmentally safe, affordable, and reliable energy services and products to the marketplace.

The PIER Program, managed by the California Energy Commission (Energy Commission), conducts public interest research, development, and demonstration (RD&D) projects to benefit California.

The PIER Program strives to conduct the most promising public interest energy research by partnering with RD&D entities, including individuals, businesses, utilities, and public or private research institutions.

PIER funding efforts are focused on the following RD&D program areas:

Buildings End-Use Energy Efficiency

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Energy Systems Integration

Environmentally Preferred Advanced Generation

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Renewable Energy Technologies

Transportation

CERTS Microgrid Laboratory Test Bed is the final report for the CERTS Microgrid Laboratory Test Bed project (contract number 500-03-024) conducted by CERTS. The information from this project contributes to PIER's Energy Systems Integration Program.

For more information about the PIER Program, please visit the Energy Commission's website at www.energy.ca.gov/pier or contact the Energy Commission at 916-654-5164.

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Abstract

The objective of the CERTS Microgrid Laboratory Test Bed project was to enhance the ease of integrating small energy sources into a microgrid. The project accomplished this objective by developing and demonstrating three advanced techniques, collectively referred to as the CERTS Microgrid concept, that significantly reduce the level of custom field engineering needed to operate microgrids consisting of small generating sources. The techniques comprising the CERTS Microgrid concept are: 1) a method for effecting automatic and seamless transitions between grid-connected and islanded modes of operation; 2) an approach to electrical protection within the microgrid that does not depend on high fault currents; and 3) a method for microgrid control that achieves voltage and frequency stability under islanded conditions without requiring high-speed communications.

The techniques were demonstrated at a full-scale test bed built near Columbus, Ohio and operated by American Electric Power. The testing fully confirmed earlier research that had been conducted initially through analytical simulations, then through laboratory emulations, and finally through factory acceptance testing of individual microgrid components. The islanding and resynchronization method met all Institute of Electrical and Electronics Engineers 1547 and power quality requirements. The electrical protection system was able to distinguish between normal and faulted operation. The controls were found to be robust under all conditions, including difficult motor starts.

The results from these tests are expected to lead to additional testing of enhancements to the basic techniques at the test bed to improve the business case for microgrid technologies, as well to field demonstrations involving microgrids that involve one or more of the CERTS Microgrid concepts.

Keywords: CERTS, microgrid, control protection, electrical protection, voltage and frequency stability control, inverter, distributed energy resources, distributed generation, distributed resource, islanding.

Executive Summary

Evolutionary changes in the regulatory and operational climate of traditional electric utilities and the emergence of smaller generating systems, including internal combustion engines, microturbines, photovoltaics, and fuel cells, have opened new opportunities for electricity users to generate power on site. In this context, distributed energy resources – small power generators typically located at sites where the energy (both electric and thermal) they generate is used – are a promising option to meet growing customer needs for economic and reliable electric power. In addition to generators, the distributed energy resources portfolio also includes energy storage, and load control. Organizing all of these resources into microgrids is a promising way to capture smaller distributed energy resources' significant potential to meet customers' and utilities' needs.

A key feature of a microgrid, is its ability, during a utility grid disturbance, to separate and isolate itself from the utility seamlessly with little or no disruption to the loads within the microgrid (e.g., in the CERTS Microgrid concept, no impacts on power quality). Then, when the utility grid returns to normal, the microgrid automatically resynchronizes and reconnects itself to the grid, in an equally seamless fashion.

The CERTS Microgrid concept seeks to provide this technically challenging functionality without extensive (i.e., expensive) custom engineering. In addition, the design of the CERTS Microgrid also provides high system reliability and great flexibility in the placement of distributed generation within the microgrid. The CERTS Microgrid is intended to offer these functionalities at much lower costs than traditional approaches by incorporating *peer-to-peer* and *plug-and-play* concepts for each component within the microgrid.

The peer-to-peer concept insures that no single component, such as a master controller or a central storage unit, is required for operation of the microgrid. Therefore, by its very design, the CERTS Microgrid can continue operating with loss of an individual component or generator. (With one additional source, (N+1) it can insure even higher levels of reliability.)

The plug-and-play concept means that a distributed energy resources unit can be placed at any point within the microgrid without re-engineering its controls. The plug-and-play functionality is similar to the flexibility one has with home appliances. That is, just as an appliance can be plugged in wherever there is an outlet, one can similarly locate distributed energy resources units at any location within a facility or building where they might be most needed. This is in sharp contrast to the traditional model, which clusters distributed generation at a single point in order to make the electrical integration tasks simpler. In combined heat and power applications, the plug-and-play model facilitates placing distributed energy resources immediately adjacent to heat loads, thereby allowing more effective use of waste heat without a complex heat distribution system, such as steam and chilled water pipes, and the energy losses associated with them.

A critical feature of the CERTS Microgrid is its presentation to the surrounding distribution grid as a single self-controlled entity. A CERTS Microgrid appears to the grid as indistinguishable from other customer sites that do not include DER. This presentation means that the microgrid

avoids many of the current concerns associated with integrating DER, such as how many DER the system can tolerate before their collective electrical impact begins to create problems like excessive current flows into faults and voltage fluctuations.

These functionalities are provided through three advanced techniques comprising the CERTS Microgrid concept, including: 1) a method for effecting automatic and seamless transitions between grid-connected and islanded modes of operation; 2) an approach to electrical protection within the microgrid that does not depend on high fault currents; and 3) a method for microgrid control that achieves voltage and frequency stability under islanded conditions without requiring high-speed communications.

The techniques were demonstrated at a full-scale test bed built near Columbus, Ohio and operated by American Electric Power. See Figure 1. Tecogen and its inverter manufacturer, Youtility, modified and factory tested three combined heat and power units to incorporate the CERTS Microgrid control algorithms. Northern Power Systems designed, fabricated, and factory tested a static switch that implemented CERTS Microgrid islanding and resynchronization procedures and also fabricated the other major hardware elements required, including load banks, power and control circuitry, protective relaying, and data-acquisition equipment, installed in metal-clad switchgear cabinets for protection in an outdoor location.

Five sets of tests were conducted by American Electric Power (AEP);

The first set of tests examined the operation of the static switch to determine that it and its digital signal processing control operated as designed. This included five tests of dead-bus and synchronized closing, reverse power and Institute of Electrical and Electronics Engineers (IEEE) 1547 protective relay functions. The goal was to confirm the correct operation (and thus the protection) of the static switch, which is located at the interface between the protected and unprotected portions of the microgrid.

The second set of tests examined a preliminary set of faults (i.e., overload simulating a high impedance fault) within the microgrid to ensure protection and safety of the test bed, prior to performing other planned tests. The fault condition tests were intended to cover the basic concepts of the protection design and to study its effectiveness (e.g., zero-sequence, negative-sequence and residual currents for line-to-ground faults; negative-sequence or (I^2T) protection for phase-to-phase faults). For the majority of these test scenarios, the static switch was expected to open first, followed by the opening of the zone breaker of the faulted zone. The goal was to test and adjust protection settings to achieve the most ideal conditions and protection design within a limited fault current system. Sixteen separate tests were conducted.

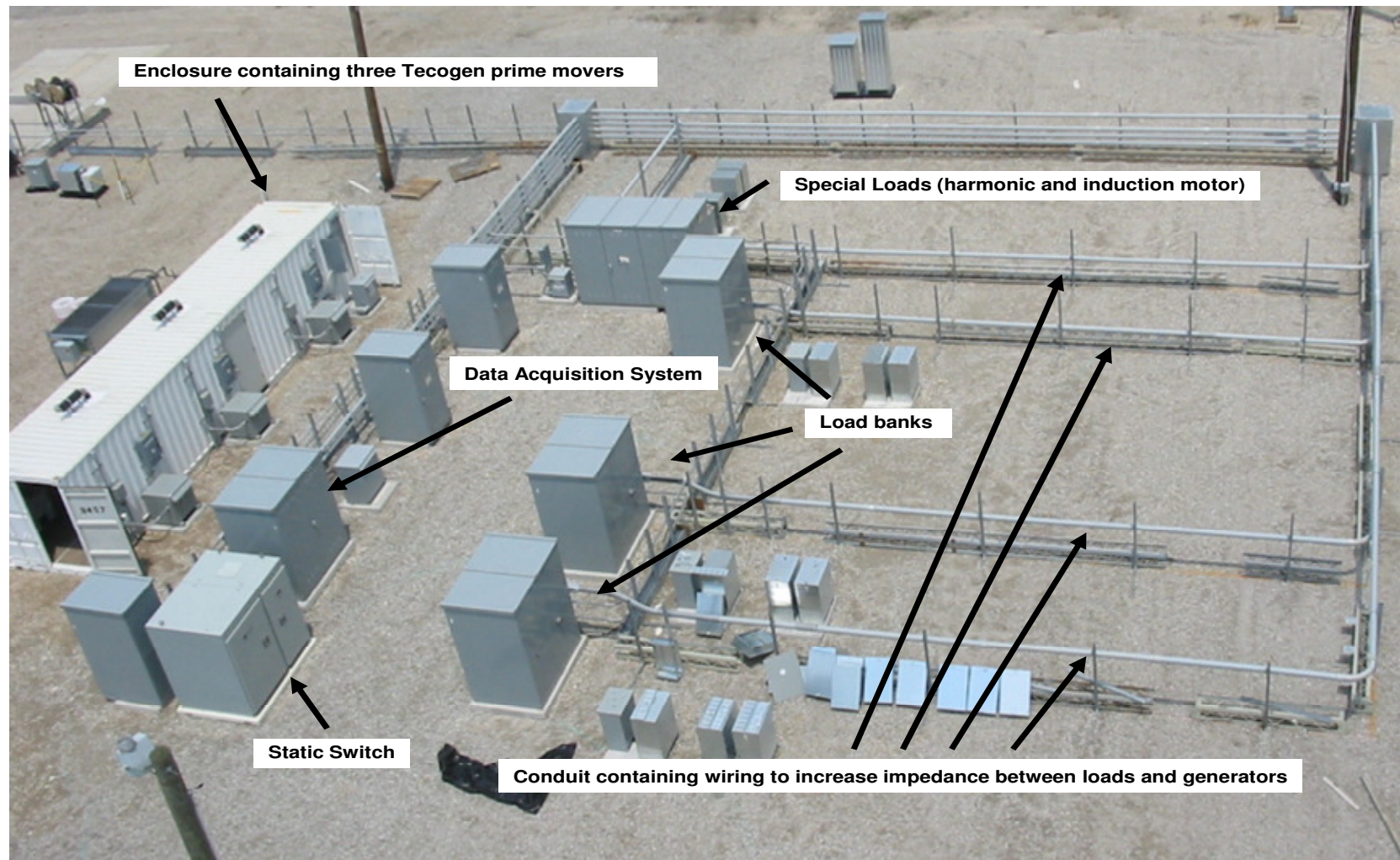


Figure 1. CERTS Microgrid Test Bed at American Electric Power

Photo Credit: American Electric Power

The third set of tests was designed to ensure that the Gen-set inverter controls were working as designed during grid-connected and islanded modes of operation. This includes unit control, zone control, and mixed power controls, in conjunction with limiting controls and synchronized closing of the static switch. These tests were based on replicating tests that had previously been conducted by Tecogen and Youtility during the factory acceptance testing of the standalone inverters, and the engine-coupled inverters. The performance goal was to observe smooth transitions of the Gen-sets response to different step conditions. Thirteen separate tests were conducted.

The fourth set of tests demonstrated the flexibility of the microgrid while both grid connected and islanded, for different loads, power flows, and utility impact. These tests employed “weak grid” inductors in the circuit simulating the microgrid connection at the end of a lengthy feeder. Three sets of tests were conducted.

The fifth and final set of testing began to explore the operational limits of the microgrid with difficult induction motor starting loads. Two primary sets of tests were conducted under “weak grid” conditions.

Detailed, standalone reports (referenced as appendices to this report) were prepared containing narrative descriptions of the purpose and performance goal for each test, along with extensive graphical and tabular summaries of the results for each test.

The testing fully confirmed earlier research that had been conducted initially through analytical simulations, then through laboratory emulations, and finally through factory acceptance testing of individual microgrid components. The islanding and resynchronization method met all IEEE 1547 and power quality requirements. The electrical protection system was able to distinguish between normal and faulted operation. The controls were found to be robust under all conditions, including difficult motor starts.

The results from these tests are expected to lead to additional testing of enhancements to the basic techniques at the test bed, to improve the business case for microgrid technologies, as well to field demonstrations involving microgrids that involve one or more of the CERTS Microgrid concepts.

1.0 Introduction

This report describes the Consortium for Electric Reliability Solutions (CERTS) Microgrid Laboratory Test Bed project, which developed and tested innovative strategies for islanding and resynchronizing microgrids with the grid, providing electrical protection within the microgrid, and controlling energy sources within the microgrid autonomously during islanded operation. Under earlier research contracts, the CERTS Microgrid team first developed these strategies using computer simulations, and then further refined them with laboratory-scale emulations. In this research contract, the team implemented them in commercial-grade hardware, with thorough testing at several stages of development, including at a full-scale test bed.

1.1. Background and Overview

Evolutionary changes in the regulatory and operational climate of traditional electric utilities and the emergence of smaller generating systems, including internal combustion engines, microturbines, photovoltaics, and fuel cells, have opened new opportunities for electricity users to generate power on site. In this context, distributed energy resources (DER) – small power resources typically located at sites where the energy (both electric and thermal) they provide is used locally – are a promising option to meet growing customer needs for economic and reliable electric power. In addition to generators, the DER portfolio also includes energy storage, and load control. Organizing all of these resources into microgrids is a promising way to capture smaller DER's significant potential to meet customers' and utilities' needs.

The CERTS Microgrid is an entirely new approach to integrating DER. Traditional approaches for integrating DER focus on the impacts on grid performance of a single or relatively small number of microsources. An example of the traditional approach to DER is the Institute of Electrical and Electronics Engineers (IEEE) Standard 1547 for Distributed Resources Interconnected with Electric Power Systems. This standard focuses on ensuring that interconnected systems will not affect the operation of the grid should problems arise on the grid. In compliance with this standard, the CERTS Microgrid is designed to seamlessly disconnect and operate as an island, separate from the grid, in case of problems and to reconnect to the grid once the problems are resolved. (Lasseter, et al. 2002. Lasseter, Piagi. 2005. Lasseter, Piagi. 2006.)

A critical feature of the CERTS Microgrid is its presentation to the surrounding distribution grid as a single, self-controlled entity. A CERTS Microgrid appears to the grid as indistinguishable from other customer sites that do not include DER. This presentation means that the microgrid avoids many of the current concerns associated with integrating DER, such as how many DER the system can tolerate before their collective electrical impact begins to create problems like excessive current flows into faults and voltage fluctuations. The CERTS Microgrid architecture insures that the microgrid will be a good citizen within the bulk power provider network, complying with grid rules and doing no harm beyond what would be acceptable from any existing customer. In return for appropriate compensation, the microgrid could provide interruptible load. Although technical barriers currently discourage it, the microgrid could also be a small source of power or ancillary services. The benefits it could offer to the distribution

system include; congestion relief, postponement of new generation or delivery capacity, rapid response to load changes, and local voltage support.

A key feature of a microgrid is its ability, during a utility grid disturbance, to separate and isolate itself from the utility seamlessly with little or no disruption to the loads within the microgrid (e.g., in the CERTS Microgrid concept, with no impact on power quality). Then, when the utility grid returns to normal, the microgrid automatically resynchronizes and reconnects itself in an equally seamless fashion.

What is unique about the CERTS Microgrid is that it can provide this technically challenging functionality without extensive (i.e., expensive) custom engineering. In addition, the design of the CERTS Microgrid also provides high system reliability and great flexibility in the placement of distributed generation within the microgrid. The CERTS Microgrid is intended to offer these functionalities at much lower costs than traditional approaches by incorporating *peer-to-peer* and *plug-and-play* concepts for each component within the microgrid.

The peer-to-peer concept insures that no single component, such as a master controller or a central storage unit, is required for operation of the microgrid. Therefore, by its very design, the CERTS Microgrid can continue operating with loss of an individual component or generator. (With one additional source, (N+1) it can insure even higher levels of reliability.)

The plug-and-play concept means that a DER unit can be placed at any point within the microgrid without re-engineering its controls. The plug-and-play functionality is similar to the flexibility one has with home appliances. That is, just as an appliance can be plugged in wherever there is an outlet, one can similarly locate DER units at any location within a facility or building where they might be most needed. This is in sharp contrast to the traditional model, which clusters DG at a single point in order to make the electrical integration tasks simpler. In combined heat and power (CHP) applications, the plug-and-play model facilitates placing DER immediately adjacent to heat loads, thereby allowing more effective use of waste heat without a complex heat distribution system, such as steam and chilled water pipes, and the energy losses associated with them.

These functionalities are enabled by three innovations: First, the CERTS Microgrid concept relies on embedding intelligence in the interface between the microsources and the surrounding microgrid.¹ This innovation enables autonomous operation of each microsource without high-speed communication or hierarchical control among microsources. This innovation is the key toward enabling a plug-and-play environment in which many microsources can operate harmoniously with one another with a minimum of expensive, custom site engineering.

¹ For pragmatic reasons of availability and controllability, this CERTS effort initially focused on small internal combustion (IC) engines. All DER technologies, especially those that rely on power electronic interfaces, including microturbines, fuel cells, photovoltaics, and energy storage, are candidates for inclusion in microgrids based on CERTS Microgrid concepts.

Second, as a result of enabling an environment in which, in principle, any number of microsources might operate within a single microgrid, the CERTS Microgrid concept also incorporates an intelligent static switch for rapid disconnect and resynchronization of the entire microgrid to the larger, utility grid at the point of common coupling (PCC). A single, intelligent switch is innovative because it is a much more economic alternative to providing this functionality at each individual microsource.

Third, the CERTS Microgrid includes an innovative, additional level of protective relaying within the microgrid that complements traditional protection. The approach addresses that fact that power electronic interfaces can, by design, limit the fault current available to detect system faults, which is the traditional means used for detecting faults within an electrical network. Thus, while a microgrid can use bi-directional over-current protection devices when connected to the utility, it cannot rely on these approaches when the microgrid is islanded. The CERTS Microgrid protection scheme uses sequence components to detect low-fault currents in utility-connected and islanded operation. This protection scheme allows for plug-and-play without changing the existing over-current devices on the electrical system.

The development and testing of the CERTS Microgrid concept is the culmination of over 7 years of research efforts supported by both the U.S. Department of Energy and (DOE) the California Energy Commission (Energy Commission). In 2001, the DOE provided research support to develop the initial CERTS Microgrid concept. In 2002, the Energy Commission began providing research support to demonstrate the CERTS Microgrid concept. Under prior Energy Commission Contract # 150-99-003, Tasks 2.4 and 2.7, in the area of Distributed Energy Resources Integration, the CERTS team: 1) conducted analytical simulations of aspects of the concept (Lasseter, et. al. 2002); 2) prepared the design for test bed where a full-scale demonstration of the concepts could be tested (Appendix A. Test Bed Design Schematics); and 3) completed a review of potential sites and research partners where the test bed could be built (Akhil, et. al. 2002).

This document is the final report for the testing that has been conducted at the test bed.

The CERTS Microgrid Laboratory Test Bed project team initially included Lawrence Berkeley National Laboratory (LBNL); Sandia National Laboratory (SNL); the University of Wisconsin (UW); and Northern Power Systems (NPS), which designs, builds and installs electric power systems. Through this project, the CERTS team was expanded to include Tecogen, Inc., a manufacturer of engine-driven cooling and combined heat and power (CHP) systems, and Youtility, a supplier of power electronic systems for distributed power. In addition, American Electric Power (AEP), one of the largest electric utilities in the United States, delivering electricity to more than 5 million customers in 11 states, was selected by the team to host the test bed and conduct the tests.

The CERTS team was aided throughout the research process by a Technical Advisory Committee (TAC) consisting of representatives from 1) the DOE's Office of Electricity Delivery and Energy Reliability; 2) two major California electric utilities, Pacific Gas and Electric (PG&E) and Southern California Edison (SCE) with expertise in interconnection of distributed

generation; 3) the National Renewable Energy Laboratory (NREL) who manage aspects of the IEEE 1547 standards development process; 4) the Electric Power Research Institute (EPRI) with expertise in power quality; and 5) an independent consultant with expertise in power electronics.

1.2. Project Objectives

The objectives of this project were to:

- Demonstrate stable operation of the CERTS control algorithms during a variety of conditions including:
- Transitions between utility-interconnected and islanded operation
- Islanded operation that involved such traditionally difficult loads as motor starting
- Demonstrate the ability to detect faults within the microgrid under a variety of conditions when either interconnected to the utility or islanded

The CERTS Microgrid Laboratory Test Bed project meets the PIER Goal of Improving the Reliability/Quality of California's Electricity by creating technologies and control strategies needed to capture the full potential of DER to improve the reliability and quality of the California interconnected power system. This project also meets the secondary goal of Improving the Energy Cost/Value of California's Electricity by lowering the cost of power delivery.

1.3. Report Organization

The CERTS Microgrid Laboratory Test Bed project consists of one technical task, CERTS Microgrid Laboratory Test Bed, with four Subtasks and five Sub-subtasks, as follows:

Subtask 2.1: Select a laboratory test bed

Subtask 2.2: Prepare equipment for the test bed

Sub-subtask 2.2.1: Prepare three prime movers and inverters for the test bed, including factory acceptance testing

Sub-subtask 2.2.2: Design, fabricate and factory test other test bed equipment, including the static switch

Subtask 2.3: Conduct tests of the CERTS Microgrid concept at the test bed

Sub-subtask 2.3.1 Prepare the test bed for testing

Sub-subtask 2.3.2 Conduct tests of the CERTS Microgrid concepts

Sub-subtask 2.3.3 Prepare a microgrid protective relaying report

Subtask 2.4 Plan a field demonstration of the CERTS Microgrid concept

The next two major sections of this report, 2.0 Project Approach and 3.0 Project Outcomes, follow this Subtask and Sub-subtask structure.

The report is supplemented by a number of stand-alone technical appendices that provide additional information and details on the results from all subtasks and sub-subtasks of this project. Several, separate appendices were required to organize voluminous tabular and graphical summaries of the data collected from each of the many tests conducted at the test bed.

2.0 Project Approach

The CERTS Microgrid Laboratory Test Bed project implemented the CERTS Microgrid concept and test bed design initiated under Energy Commission Contract #150-99-003, tasks 2.4 and 2.7, to develop tools and techniques for significant integration of distributed technologies in support of electricity reliability.

The subsections below describe the approach taken under each Subtask and Sub-subtask and in the project.

2.1. Test Bed Selection (Subtask 2.1)

The goal of this task was to select and execute a contract with a facility to conduct a full-scale test-bed demonstration of CERTS Microgrid concepts. The task included developing criteria for selecting a testing facility and, using information from past reviews conducted by the team to identify candidate sites, working with the Technical Advisory Committee (TAC) and Energy Commission Contract Manager to select the most appropriate site. Finally, following the Commission Contract Manager's approval, LBNL was to execute a subcontract with the Energy Commission-approved facility.

2.2. Equipment Preparation (Subtask 2.2)

The goal of this subtask was to enter into contracts with a microsource manufacturer, Tecogen/Youtility, to prepare three microsource prime movers with modified inverters and with a DER engineering firm, Northern Power Systems (NPS), to fabricate test bed hardware including a static switch, for use in the laboratory test bed demonstration (Subtask 2.3).

The first phase of work required Tecogen/Youtility to upgrade the current design of its inverter to incorporate CERTS Microgrid control algorithms and to conduct extensive factory tests of the modified microsource prime movers and inverters (Sub-subtask 2.2.1). The machines had to be as identical to one other as possible so that impacts from machines with differing characteristics did not mask important observations about performance, especially during transients, within the test bed. Because of the technical requirements for the test bed prime movers, the supplier had to be able to dedicate a small, technically skilled team to this project. The supplier also had to have the flexibility to revisit and rebuild aspects of the units because the team expected that initial testing would reveal the need for modifications.

In the original Energy Commission contract, Capstone Microturbines was expected to supply the modified microsource prime movers. However, Capstone Microturbines declined to execute a contract with LBNL due to a change in business priorities and withdrew from the project. Following an introduction provided by the Energy Commission contract manager, the team partnered with Tecogen/Youtility to supply the modified prime mover microsources and inverters. Aspects of the laboratory test bed design were modified by NPS to accommodate this change in prime movers.

The second phase of work required NPS to develop and conduct factory tests of a static switch that implements the CERTS Microgrid islanding and resynchronization procedures (Sub-

subtask 2.2.2). As an additional element of the second phase of work, NPS also fabricated the major electrical components required by the test bed, such as load banks and emulators, switchgear, and the data acquisition system (DAS). NPS was well-qualified to conduct this work because they had, under a previous Energy Commission contract with CERTS, prepared the complete design of the laboratory test bed.

2.3. Laboratory Tests (Subtask 2.3)

The goal of this subtask was to conduct tests of the CERTS Microgrid concept. That is, the laboratory test facility selected in Subtask 2.1 was to build the test bed and conduct tests of the test bed equipment, prime movers, and static switch prepared under Subtask 2.2. This subtask was conducted through three sub-subtasks.

The goal of sub-subtask 2.3.1 was to prepare the test bed for conducting the tests. This involved preparation of the physical test bed site following the design of the test bed, which was prepared under an earlier contract. (See Figures 2, 3, and 4, which are based on Appendix A, Test Bed Design Schematics). The tasks included erection of enclosures to house the microsources and associated facilities to cool the engines in operation and the laying out of conduits and associated wiring to interconnect the microgrid elements. Finally, the task involved installing the cabinets assembled by NPS as well as the microsources prepared by Tecogen/Youtility. See Figure 1.

The goal of sub-subtask 2.3.2 was to conduct a large number of tests exercising all functions of the CERTS Microgrid concept. This goal was accomplished in three phases. First, a detailed test plan was developed. Second, the tests were executed following the test plan. Third, the test results were analyzed and assessed with respect to the test plan and overall project objectives.

The CERTS team, led by NPS, developed a comprehensive list of tests that would exercise every aspect of the CERTS Microgrid concept. The tests were presented to and refined through discussions with the TAC. After the list of tests was deemed complete, AEP developed “registered” test procedure, following AEP corporate rules that would meet all testing needs safely. This registered test procedure is presented in Appendix B. CERTS Microgrid Testbed – Test Plan.

The registered test procedure contains ten sections. The first five are procedural. Sections six through ten refer to actual tests in which measurements are recorded. The tests were conducted by AEP in accordance with the registered test procedure. Testing was conducted sequentially, one section at a time.

Prior to each test day, the person in charge performed a job safety briefing including an inspection of the barricades and test setup for safety and compliance. A minimum of two people were on-site during each planned test

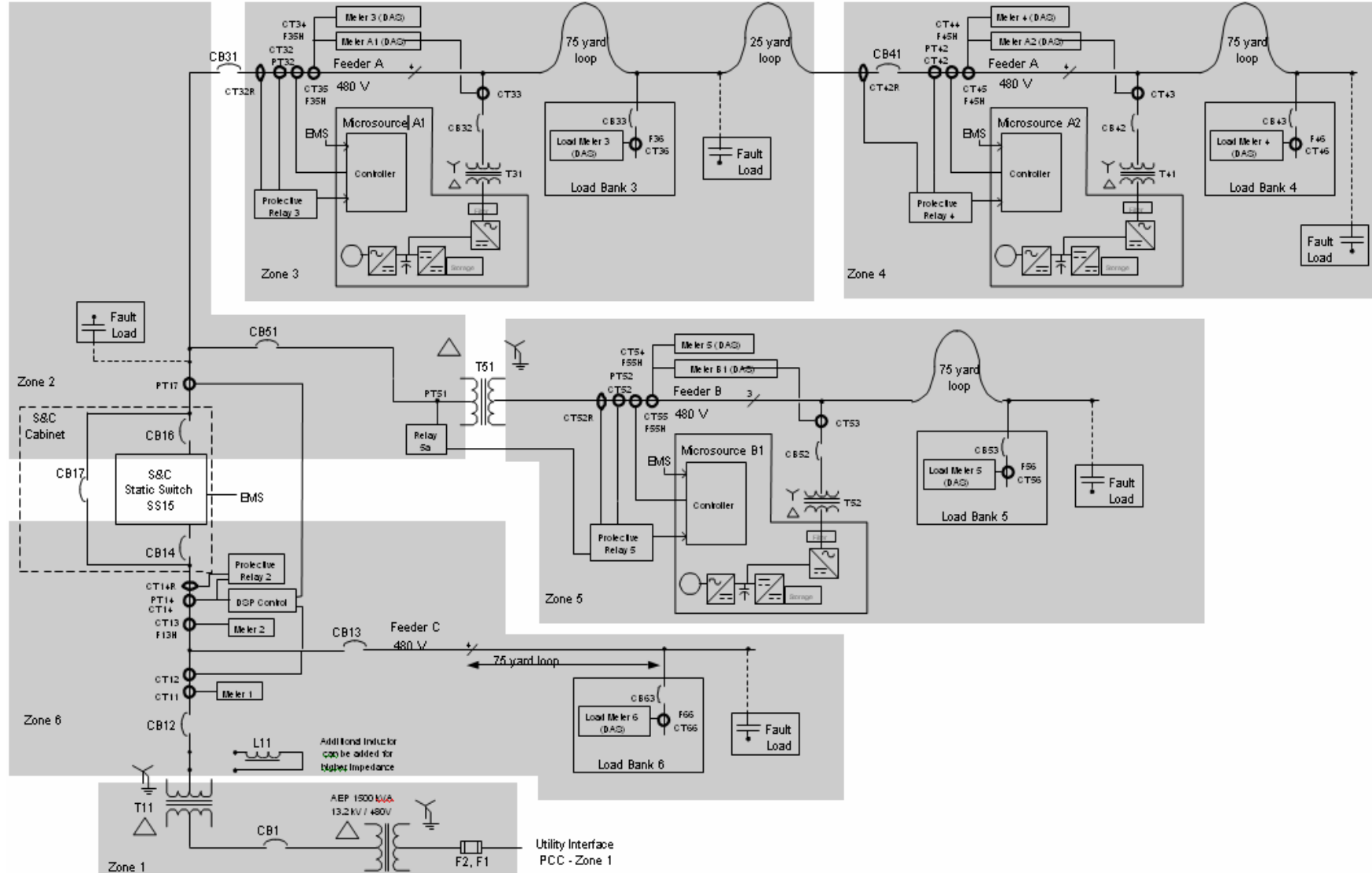


Figure 2. One-Line Diagram of CERTS Microgrid Test Bed

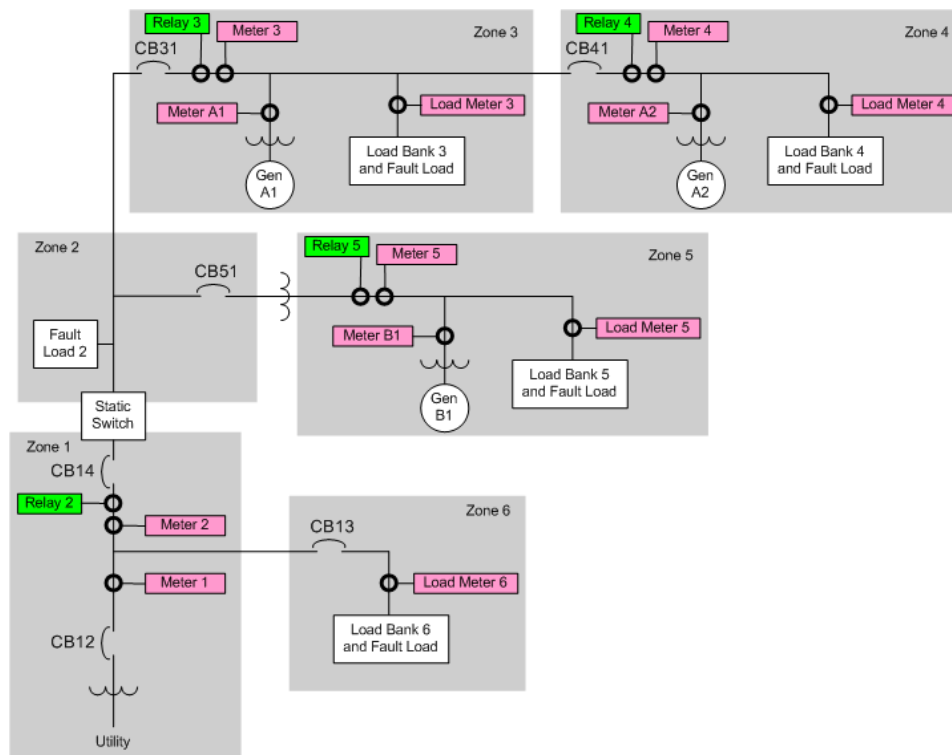


Figure 3. One-Line Diagram with Meter and Relay Locations CERTS Microgrid Test Bed

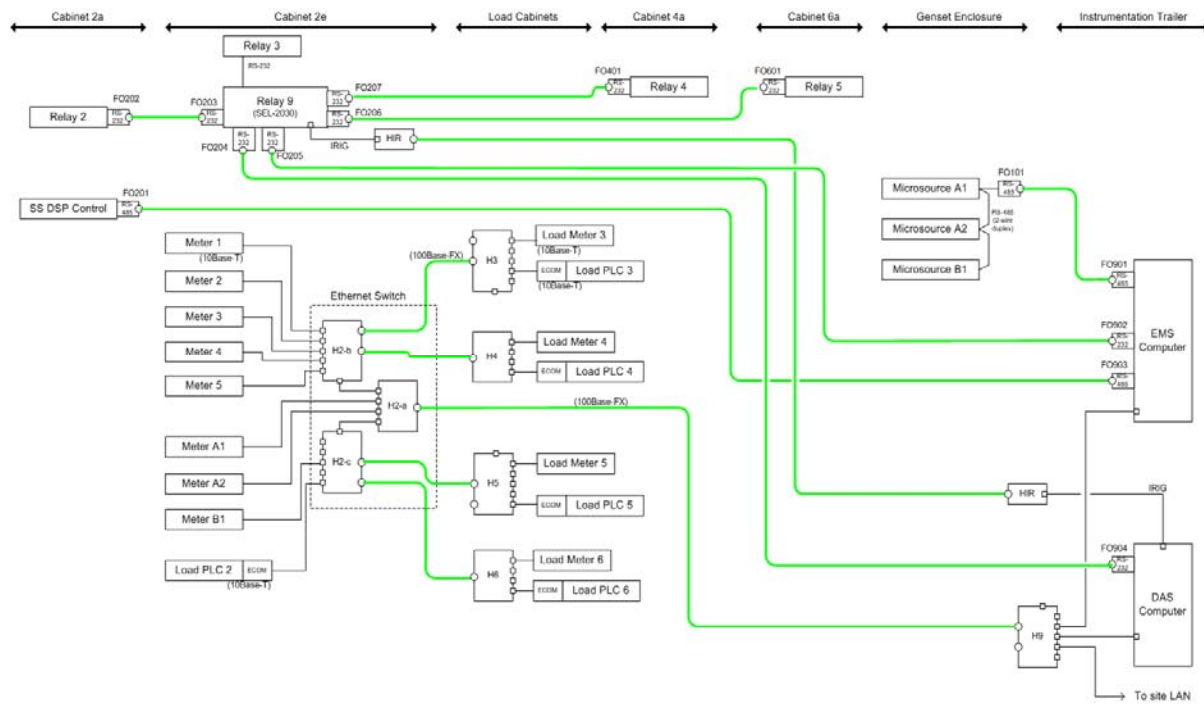


Figure 4. Diagram of DAS & EMS Data networks

Visual and audible alarms warned persons that energized testing was being performed in the Microgrid Test Bed area. The visual alarm consisted of a portable red flashing light, located between the Control Trailer and Gen-set Enclosure. An audible alarm, consisting of a portable wireless motion detector, was located at the front gate of the Walnut Test Site with the fence gate “Closed,” not locked, and audible alarm in the trailer operational during test(s).

Barricades were set up around the Microgrid Test Bed area (i.e., saw-horse style barricades with a red plastic chain surrounded the test area containing the Gen-set Enclosure, Microgrid switching cabinets, plus load and fault bank cabinets).

Prior to performing tests, the Test Engineer or Technical Consultant verified that all personnel and visitors were properly protected and in assigned locations. Personnel were in or adjacent to the Control Trailer while tests were being performed. All nonessential personnel either left the main site or were sheltered in the Control Trailer.

The first set of tests (Section 6 of the test plan) examined the operation of the static switch to determine that it and its digital signal processing (DSP) control operated as designed. The goal was to confirm the correct operation (and thus the protection) of the static switch, which is located at the interface between the protected and unprotected portions of the microgrid. Successful completion of these tests was a prerequisite to performing subsequent tests in the test plan.

The tests were designed to check control and operation of the static switch, basic power and voltage control of the Gen-sets, and a preliminary check of the protection scheme. They included five tests of dead-bus and synchronized closing, reverse power and IEEE 1547 protective relay functions. The switch functions were tested with a single Gen-set A1 online. The measurements taken were unique to each test. Waveform and RMS data from Meter 2 were of prime interest.

The second set of tests (Section 7 of the test plan) examined a preliminary set of fault (i.e., overload simulating a fault) condition tests to ensure protection and safety of the test bed, prior to performing other planned tests. The goal was to confirm the new protection design developed in Task 2.3.3. This goal was to be accomplished by testing and adjusting protection settings to achieve the most ideal conditions and protection design. The tests included inductor L11 in the circuit, reflecting “weak grid” conditions. Sixteen separate tests were conducted.

The fault (i.e., overload simulating a fault) condition tests were intended to cover the basic concept of the protection design and to study its effectiveness (e.g., zero-sequence, negative-sequence and residual currents for line-to-ground faults; negative-sequence or (I^2t) protection for phase-to-phase faults). For the majority of these test scenarios, the static switch was expected to “OPEN” first, followed by the zone breaker of the faulted zone.

During each fault event waveforms of phase currents and line-to-neutral voltages at all Relay locations (i.e., Relays 2, 3, 4 & 5) were recorded. The relay element that caused the “TRIP” with trip times for each relay relative to when the fault condition was applied was also recorded.

Two power control modes were defined for the third and fourth sets of tests:

Unit Power Control Mode controls the amount of power (i.e., kW) being injected into the Zone from the Gen-set being controlled.

Zone Power Control Mode controls the amount of power (i.e., kW) entering/exiting the Zone using the Gen-set to offset the difference in that Zone.

The third set of tests (Section 8 of the test plan) was designed to ensure that the Gen-set inverter controls were working as designed. This includes unit control, zone control, and mixed power controls, in conjunction with limit controls and synchronized closing of the static switch. These tests were based on replicating tests that had previously been conducted by Tecogen and Youtility during the factory acceptance testing of the standalone inverters, and the engine coupled inverters. The performance goal was to observe smooth transitions of the Gen-sets response to different step conditions (i.e., static switch “OPEN”/ “CLOSE” and load steps). Thirteen separate tests were conducted.

Several measurements were made for each test:

- Sources –Injected power (kW), reactive load (kVAr), frequency (freq), and voltage (V) for each Gen-set (i.e., A1p, A2p and B1p).
- Zone input power flow into Zones 3 (A1z), 4 (A2z), 5 (B1z) and 6.
- Loads - Voltage at Load Bank 3 (L3), 4 (L4), 5 (L5), and 6 (L6).
- Static Switch - Power (kW) and current (I) through the static switch.
- Static Switch Control Signal: Forced “OPEN” and release to allow self synchronization.
- Voltage (V) and frequency (Freq) difference across the static switch.

The fourth set of tests (Section 9 of the test plan) demonstrated the flexibility of the microgrid both grid connected and islanded for different loads, power flows and impact on the utility. The tests included the “weak grid” inductors (i.e., L11) in the circuit. Three sets of tests were conducted.

The measurements taken for these tests involved collecting RMS data for V, I, kW, kVAr, and Freq for each flow change at the following points:

- Meter 1 –V, I, kW, kVAr for the utility connection
- Meter 2 - V, I, kW, kVAr and utility-side V and Freq
- Meter 3 - V, I, kW, and kVAr for Feeder A and Microgrid side V and Freq
- Meter A1p – V, I, kW, kVAr for Gen-set A1
- Load Meter 3 – V, I, Zone 3 load kW and kVAr
- Meter 4 – V, I, kW, kVAr for Zone 4
- Meter A2p – V, I, kW, kVAr for Gen-set A2
- Load Meter 4 – V, I, Zone 4 load kW and kVAr
- Meter 5 – V, I, kW, kVAr for Feeder B

- Meter B1p – V, I, kW, kVAr for Gen-set B1
- Load Meter 5 – V, I, Zone 5, Feeder B load kW and kVAr
- Load Meter 6 – V, I, Zone 6, Feeder C load kW and kVAr

In addition V and I waveform data for unexpected events and for static switch transitions.

The fifth and final set of testing (Section 10 of the test plan) began to explore the operational limits of the microgrid (i.e., power quality, protection and inverter limits). Two primary sets of tests were conducted under “weak grid” conditions; the first involved induction motor starting loads under balanced and unbalanced load conditions; the second involved only unbalanced loads.

The measurements collected included the following:

- RMS data for kW, kVAr V, and I injected by each Gen-set
- Freq at each connection point
- V and I from Meters 1 - 5, and Load Meters 3 - 6

The analysis of the test results consisted of comparing test results to findings from earlier analyses of CERTS Microgrid concepts. As noted, successive analysis and testing of the CERTS Microgrid concepts have include analytical simulation, laboratory-scale emulations, and factory testing of the commercial-grade hardware installed at the test bed.

A number of software tools were used to process raw test data into a format suitable for review and presentation. These included: PQView, AcSELerator QuickSet Designer, Excel, and Word. Test results were posted by AEP onto a secure website where they could be reviewed and discussed by the entire CERTS team.

Test bed results were then presented and discussed with the TAC. TAC members were also invited to review and provide comments each of the extensive reports that have been prepared detailing the results of the testing.

The goal of sub-subtask 2.3.3 was to develop an innovative approach to provide protective relaying within the microgrid. The approach addresses that fact that power electronic interfaces, by design, limit the fault current available to detect system faults, which is the traditional means for detecting faults within an electrical network. Hence, in addition to traditional protection schemes that were already in place, the CERTS team, led by University of Wisconsin, needed to design an additional level of protection for faults that occur within the microgrid. These designs were then implemented and tested as part of the tests conducted in sub-subtask 2.3.2.

2.4. Field Demonstration Planning (Subtask 2.4)

The goal of subtask 2.4 was to identify and engage one or more partners for a field demonstration of the CERTS Microgrid concept. While a field demonstration was not to be conducted in this project, it was important to engage potential partners prior to and during the

laboratory test-bed phase so that partner-specific technical or operational issues could be addressed in the test bed prior to conducting the field demonstration.

This task was a continuation of work initiated under a previous Energy Commission agreement (amendment #150-99-003, task 2.7). That contract led to preparation of a field demonstration planning and partner recruitment strategy. The current task continued the implementation of that strategy.

The approach primarily involved conducting meetings with potential field demonstration partners to brief them on the CERTS Microgrid concept and test bed prior to and during the testing. Other activities that contributed to field demonstration planning by increasing the visibility of the CERTS Microgrid concept to a wide audience included presentations and publications of the CERTS Microgrid concept in a variety of fora, including professional meetings, domestic and international conferences, and academic and trade publications. These activities directly contributed to and supported follow-up discussions with potential field demonstration partners.

3.0 Project Results

This section presents projects results from Subtasks 2.1-2.4 of the Microgrid Laboratory Test Bed project. As discussed earlier, the project produced a number of deliverables. Several of these are quite voluminous, as they contain extensive tabular and graphical summaries from each of the tests conducted at the test bed. For brevity, this report only summarizes and highlights selected findings from these deliverables. This report is supplemented by numerous, separately bound appendices, which contain these detail project findings; these appendices are referenced throughout the following discussions.

3.1. Test Bed Selection (Subtask 2.1)

The goal of Subtask 2.1 was accomplished through the selection of and execution of a contract with the American Electric Power Company to join the CERTS team to build the test bed and conduct the testing program. The steps including developing selection criteria, applying them to candidate facilities, and determining the most qualified facility.

The final test site selection criteria included the following:

1. Physical requirements
 - a) Adequate space for the test bed and generators (including safe working space around equipment)
 - b) Availability of a “stiff” distribution voltage (preferably 15kV class)
 - c) Availability of natural gas
 - d) Availability of “standard” test equipment
2. Personnel –Test engineers and technicians with appropriate experience
3. Project leader with appropriate experience
4. Corporate interest and involvement
5. Timing and availability to meet CERTS requirements
6. Utility-owned and operated site – Important for utility community acceptance of the credibility of test results
7. Accessibility of test site to interested researchers

Under an earlier Energy Commission contract 150-99-003, the CERTS team conducted a preliminary assessment of possible sites for the test bed.² Based on this preliminary assessment, the team applied the above criteria and identified three candidate test sites:

1. Pacific Gas and Electric (PG&E) Technology and Ecological Services, San Ramon, California;
2. Southern California Edison (SCE) Electric Vehicle Technology Center, Pomona, California
3. American Electric Power (AEP) Dolan Technology Center, Groveport, Ohio

² “Review of Test Facilities for Distributed Energy Resources” by A. Akhil, C. Marnay, and T. Lipman, SAND2003-1602, May, 2003.

Input from the TAC and discussions with the Energy Commission contract manager on the list of final candidate test sites and the test site selection criteria led the team to modify the scope of sub-subtask 2.2.2 to have NPS also fabricate the majority of the test bed hardware, rather than have it fabricated by the test facility. There were two reasons: First, the team determined that the test facility should be selected primarily based on its ability to conduct the tests, not based on its ability to fabricate test bed hardware. Second, NPS was uniquely qualified to fabricate the equipment because it had designed the equipment, as part of its preparation of the overall test bed design (conducted as part of an earlier Energy Commission contract 150-99-003).

With this revised scope for the test facility, the team then sent a questionnaire to each of the three final candidate sites requesting detailed written information on four topics:

1. Required steps to prepare the physical site;
2. Equipment availability, data acquisition hardware and approach, and energy management system (EMS);
3. Personnel; and
4. Project scheduling and coordination.

At this point, PG&E indicated that would not be able to respond because it would not be able to conduct the tests within the available time, largely due to prior commitments to other Energy Commission PIER DER Integration projects. This potential conflict was acknowledged by the Energy Commission contract manager and it was agreed that PG&E should not be considered to host the tests.

The CERTS team and the Energy Commission contract manager then scheduled oral presentations from representatives from both SCE and AEP. On the basis of these presentations, the CERTS team and the Energy Commission contract manager further followed up with on-site visits to the proposed test sites at both SCE and AEP.

Following the site visits, the team recommended the selection of AEP, as the host for the test bed. The SCE site did not have a natural gas supply line and would have required extensive modifications to the electric service interconnection. The AEP site was well-suited physically, had natural gas service, and had an appropriate electric service interconnection.

In conjunction with the contract award, AEP and CERTS entered into a Memorandum of Understanding to work cooperatively in areas of mutual interest for research, development, and demonstration of distributed energy resource (DER) technology microgrids. Subsequent to the initiation of work on this Energy Commission project, CERTS and AEP have won a competitive solicitation from the U.S. Department of Energy to conduct additional tests using the microgrid equipment developed in this project.

3.2. Equipment Preparation (Subtask 2.2)

The goal of subtask 2.2 was accomplished by work led by Tecogen and their subcontractor, Youtility, to modify three Tecogen prime movers to incorporate CERTS Microgrid control algorithms (Sub-subtask 2.2.1) and by work led by NPS to fabricate a static switch that implemented CERTS islanding and resynchronization procedures and fabricate the other major hardware elements required by the CERTS laboratory test bed design. A critical element of these sub-subtasks involved detailed factory acceptance testing to confirm the performance of the equipment prior to shipment to AEP.

3.2.1. *The Prime Movers and Inverters (Sub-subtask 2.2.1)*

CERTS contracted with Tecogen to obtain three 100kW prime movers, each of which was modified to incorporate the CERTS Microgrid control algorithms. The complete systems, which were delivered and installed in the CERTS Microgrid test bed site at AEP, each included an engine/generator, a “surge module” and an inverter. See Figure 5.



Figure 5. Tecogen Prime Mover with Inverter

A critical aspect of this project was the incorporation of the CERTS Microgrid control algorithms into the inverters provided by Youtility. This required not only providing the algorithms to Youtility, but also providing Youtility with an in-depth understanding of the function of these algorithms so that they could understand the expected response, and the significance of deviations from that response, when the completed inverters were subjected to test scenarios. Providing this understanding required considerable interaction between the Youtility designer and the project’s technical director from the University of Wisconsin, Professor Robert Lasseter.

Professor Lasseter also provided Youtility with a set of test scenarios that were used to confirm correct operation of the completed inverters. These test scenarios then comprised a Youtility factory acceptance test that was performed prior to sending the inverters to Tecogen. The test report for the Youtility factory acceptance tests is included as Appendix C. Youtility Factory Test Plan Final Test Results.

The prime mover for the engine/generator is a 454 cubic inch displacement natural gas-fired V8 reciprocating engine. This engine was designed to be operated at an engine speed selected to give the best combination of fuel efficiency and response to load changes. Thus, the engine speed will not necessarily be synchronous with a 60Hz system. The electrical generator a variable AC output which is rectified to a direct current (DC) output. The inverter converts the DC to utility-synchronous AC. For this project, the inverter was modified to incorporate the CERTS Microgrid control algorithms. The surge module is an energy storage device, consisting of batteries, power electronics, and controls, which is tied to the DC bus in parallel with the electrical generator and the inverter. The purpose of the surge module is to provide instantaneous power when there is a load increase, while waiting for the engine/generator to adjust its speed to the new loading conditions. The inverters and surge modules were both supplied to Tecogen by Youtility, Inc. Tecogen integrated the entire prime mover system and performed a set of factory acceptance tests, as specified by the CERTS team, before Tecogen shipped the units to the test bed site. (See Appendix D. Tecogen 60kW Inverter-Based CHP Modules Factory Testing.)

Once at AEP's facilities, the Tecogen units were retested to ensure there had been no shipping damage. The tests confirmed that the performance of the units once installed at AEP was consistent with the factory tests. (Appendix E. Tecogen CHP Modules Commissioning Report.)

3.2.2. The Static Switch and Other Test Bed Equipment

CERTS contracted with NPS to design, fabricate, and test a static switch that implemented CERTS Microgrid islanding and resynchronization procedures and to fabricate the other major hardware elements required by the CERTS laboratory test bed design, including load banks, power and control circuitry, protective relaying, and data-acquisition equipment, installed in metal-clad switchgear cabinets for protection in an outdoor location.

NPS designed and built the controls that would allow the static switch to implement the CERTS Microgrid islanding and resynchronization procedures. The controls were implemented onto the static switch hardware associated with the Purewave uninterruptible power supply system manufactured by S&C Electric. See Figure 6. The islanding procedures consisted of trip sensing (i.e., detect and trip on IEEE 1547-specified criteria such as voltage or frequency deviations and reverse power flow) followed by disconnection (islanding) of the microgrid from the utility. The voltage-trip function included trip-characteristics required by IEEE 1547 for distributed resource interconnection, those specified by the Information Technology Industry Council for power quality, as well as a custom-voltage-versus-time-trip characteristic that could be specified by the user.

The resynchronizing function had to meet a more stringent requirement than the commonly accepted criteria of IEEE 1547. The reason for the more stringent requirement was to insure transient free transitions for power flow either into or out of the microgrid at the instant of switch closing. IEEE 1547 requires the phase difference across the switch is less than 20° before the switch can close. This phase difference is too large for our needs. We require closing at a zero phase difference. The high-speed static switch and digital signal processing (DSP), insures that the voltage phase difference a closing is zero.



Figure 6. The Static Switch

NPS tested the static switch with low-level power (i.e., signal injection) to confirm proper operation before shipping the switch to AEP. TAC members from the National Renewable Energy Laboratory shipped additional testing equipment and lent expertise to NPS in support of this testing. (Appendix F. CERTS Test Bed CERTEQUIP-V06-002, CERTS Switch, Low Power Factory Acceptance Test Report.)

Once at AEP's facilities, the switch was retested with low power to ensure there had been no shipping damage. After confirming that the static switch was in good condition, AEP performed further testing at the Dolan Test Facility to examine selected power quality issues prior to installing equipment at the test bed. (Appendix G. Summary of CERTS Microgrid Static Switch Power Quality Tests at AEP Dolan, CERTS Microgrid Static Switch Testing.)

NPS also fabricated cabinets containing all the sensing hardware for the protection and data-acquisition equipment; the circuit breakers, switches and fuses; and all the loads. The loads include a variety of resistive, inductive, capacitive and motor loads as well a six-pulse power rectifier to provide a non-linear load.

3.3. CERTS Microgrid Laboratory Tests

This section describes the preparation of the laboratory test bed for testing (Sub-subtask 2.3.1), the results of the CERTS microgrid laboratory tests (Sub-subtask 2.3.2), and the development of an approach for internal protection within the microgrid (Sub-subtask 2.3.3).

3.3.1. Prepare Laboratory Test Bed for Testing

After preparing the site, erecting supporting structures, cooling equipment, and wiring, and installing the equipment prepared by NPS and Tecogen/Youtility, AEP and Northern Power performed a field acceptance test. See Figure 1. The field acceptance testing also included exercising the complete data acquisition and control systems. After completing this testing and rectifying the minor issues that it uncovered, the team declared the test bed ready to conduct the full set of CERTS Microgrid tests, as outlined in the test plan. (Appendix H. CERTS Test Bed Design and Commissioning Lessons Learned Summary.)

3.3.2. Test of CERTS Microgrid Concepts

As described in section 2.3.2, five sets of tests were conducted. The results of these five sets of tests are contained in separate, stand-alone appendices to this report, as follows:

1. Static Switch (Section 6 of the test plan – 6 tests – Appendix I)
2. Protection (Section 7 of the test plan – 16 tests – Appendix J)
3. Reduced System (Section 8 of the test plan – 13 tests – Appendix K)
4. Power Flow Control (Section 9 of the test plan – 3 banks of tests – Appendix L)
5. Difficult Loads (Section 10 of the test plan – 1 set of motor starting tests – Appendix M)

Each appendix contains a narrative description of the purpose and performance goal for each test, along with graphical and tabular summaries of the results for each test. In addition, a sixth appendix (Appendix N) contains the test log developed by AEP during the conduct of the tests.

For brevity, this report will summarize and highlight selected findings for each of the five sets of tests. This includes listing each test conducted and its performance objective. The interested reader is referred to the individual appendices to see detailed results from each test performed.

The first set of tests (Section 6 of the test plan) examined the operation of the static switch to determine that it and its digital signal processing (DSP) control operated as designed. This included six tests of dead-bus and synchronized closing, reverse power and IEEE 1547 protective relay functions. These tests were designed to check control and operation of the static switch, basic power and voltage control of the Gen-sets, and a preliminary check of the protection scheme. The goal was to ensure that, by confirming the correct operation of the static switch, which is located at the interface (and thus serves as the protection) between the unprotected and protected portions of the microgrid, was ready to perform the remaining tests.

A synchronized closing test of the static switch was required to verify that when conditions were within synchronization limits set in the EMS, the static switch performed a synchronized close and thus provided a smooth connection transition. The dead-bus bus (de-energized bus) reclose test's goal was to verify that the static switch can close when de-energized bus conditions exist on the Gen-set side of the static switch; and that the dead-bus reclose algorithm requires user interaction (i.e., Operator needs to "Enable" the dead-bus reclose using pushbutton in the EMS).

The reverse power tests consisted of three tests: three-phase reverse power condition test, single-phase reverse power condition test, and anti-islanding Micro-grid settings reset test. Both three-phase and single-phase reverse power condition tests were required to verify the reverse power functionality of the static switch and confirm that the static switch islands the microgrid for a three-phase or single-phase reverse power conditions. The anti-islanding Micro-grid settings reset test was needed to verify that if a reverse power event occurred, due to a mismatch of Gen-set settings (i.e., total Gen-set power is greater than Microgrid load), the static switch will lockout and go to the "Fault" state, where user interaction is required.

The next goal was to verify the reconnection timers of the static switch (i.e., set by default at 300 seconds based on IEEE Standard 1547-2003). The length of time is programmed into the control system and designed to prevent reconnection until after the utility source voltage returns to nominal steady state conditions.

Table 1 summarizes the test performance goals and results from each of these tests.

Test Description	Performance Goal	Results
6.1. Start-up system, synchronized closing	Verification that when conditions are appropriate (within synchronization limits set in the EMS), the switch can perform a synchronized closing and thus give smooth closing transitions.	When electrical system conditions met established criteria, the static switch performed a synchronized "Close". A smooth voltage transition occurred from island to utility-connected mode.
6.2. Reverse power, grid islanding (IEEE 1547, loss of utility service)	Verify the reverse power functionality of the static switch and confirm that the static switch islands the Microgrid for a reverse power condition due to an upstream utility operation at the PCC. Once the utility voltage returns to the IEEE 1547 limits, verify the proper operations of the reconnection timers (set by default to 300 seconds based on IEEE 1547 standard).	The static switch islanded the microgrid from the utility grid due to an undervoltage condition. This occurred after the utility feeder opened separating the microgrid with 500kW of feeder load which was supplied by Gen-set A1 until the static switch opened. Once the static switch opened Gen-set A1 continued serving the protected load within the microgrid. After 300 seconds, the static switch synchronized and closed back into the utility grid with a smooth transition.
6.3. Reverse power, single-phase (IEEE 1547 voltage events)	Verification that the static switch islands the Microgrid when a reverse power condition, due an open-phase occurs. Note there are no single-phase breakers to disconnect the utility; reducing the load on one phase of the Microgrid will simulate the "open phase" condition. This condition does not properly test the reconnection logic, after an open phase, since the utility voltage will still be present on all three phases (i.e., test didn't really disconnected a phase).	When A-phase of Load Bank 6 was reduced near 0kW a single-phase reverse power condition was created and the static switch opened. The microgrid remained electrically stable, matching generation with load demand. Once the A-phase of Load Bank 6 was increased above the reverse power threshold and the static switch was reset a synchronized closed occurred.
6.4. Reverse power, anti-islanding microgrid settings reset	Verify that if a reverse power event occurs, due to a mismatch of Gen-set settings (Total Gen-set power > Microgrid load), the static switch will lockout and go to the "Fault" state, where user interaction is required.	Load was reduced within the microgrid which caused the static switch to open on a reverse power condition. The Gen-sets picked up the load within the microgrid. All loads were reset and the static switch synchronized and closed back into the utility.

6.5. De-energized bus (dead bus) reclose	Verify that the static switch can close when de-energized bus conditions (< 15V) on the DG side are measured and that the Dead Bus Reclose algorithm requires user interaction (i.e., Operator needs to “Enable” the Dead Bus Reclose using pushbutton in the EMS).	The static switch synchronized and closed into the utility grid with less than 15V on the DG side.
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Table 1. Static Switch Testing Summary

The second set of tests (Section 7 of the test plan) examined a preliminary set of fault (i.e., overload simulating a fault) condition tests to ensure protection and safety of the test bed, prior to performing other planned tests. The goal was to test and adjust protection settings to achieve the most ideal conditions and protection design. The tests included inductor L11 in the circuit, reflecting “weak grid” conditions. Sixteen separate tests were conducted. The fault (i.e., overload simulating a fault) condition tests were intended to cover the basic concept of the protection design and to study its effectiveness (e.g., zero-sequence, negative-sequence and residual currents for line-to-ground faults; negative-sequence or (I^2t) protection for phase-to-phase faults). For the majority of these test scenarios, the static switch was expected to “OPEN” first, followed by the zone breaker of the affected zone. The objective was to confirm the protective action detailed in the Protection document developed in Task 2.3.3.

Test 7.1 induced a three-phase-to-ground balanced overload fault condition in Zone 4 to verify the I^2t protection and a single line-to-ground fault condition in Zone 4 to verify zero-sequence, negative-sequence or residual over-current protection. Zone 3 and Zone 5 were tested similar to Zone 4 by introducing a three-phase-to-ground balanced overload fault and a single line-to-ground fault conditions in the zones, verifying the protection scheme in Test 7.2 (Zone 3) and Test 7.3 (Zone 5). During the 7.1, 7.2 and 7.3 tests, all three Gen-sets were off-line and the CERTS Microgrid was connected to the utility. Test 7.4 tested a three-phase-to-ground balanced overload fault condition in Zone 4 with Gen-sets A1 and A2 operating in-parallel with the utility grid to verify I^2t protection, plus to confirm a reverse power event after the zone breaker “opens”.

Test 7.5 through Test 7.10 involved applying a single line-to-ground overload fault condition in each Zone, located beyond the static switch, while connected to the utility grid. Each one of the six tests differs from one another by which Gen-sets are on-line during the fault, which phase is faulted, and in which zone the fault is applied. These tests were designed to verify zero-sequence, negative-sequence or residual over-current protection settings. Test 7.5 verified the protection in Zone 3 by applying a single line-to-ground overload fault condition with Gen-sets A1 operating in parallel with the utility grid. Test 7.6 tested a single line-to-ground overload fault condition in Zone 3 with Gen-sets A1 and A2 operating in parallel with the utility grid. Test 7.7 tested a single line-to-ground overload fault condition in Zone 5 with Gen-set B1 operating in parallel with the utility grid. Test 7.8 tested a single line-to-ground overload fault condition in Zone 5 with Gen-sets A1 and B1 operating in parallel with the utility grid. Test 7.9 tested a single line-to-ground overload fault condition in Zone 4 with Gen-sets A1 and A2 operating in parallel with the utility grid. Test 7.10 tested a single line-to-ground overload fault condition in Zone 2 with Gen-sets A1 and B1 operating in parallel with the utility grid.

Tests 7.11 and 7.12 both applied a single line-to-ground overload fault condition in Zone 6 while connected to the utility. Test 7.11 involved only Gen-set A1 operating in parallel with the grid; and Test 7.12 involved Gen-sets A1 and B1 operating in-parallel with the grid. Both tests were designed to verify the I^2t protection of the breaker in Zone 6.

The four tests, 7.13 – 7.16, applied a line-to-line overload fault condition in one of the five zones beyond the static switch with a combination of two Gen-sets, operating in parallel with the

utility grid. These tests were designed to test negative-sequence, I^2t protection or residual over-current protection settings. Test 7.13 tested a phase-to-phase overload fault condition in Zone 3 with Gen-sets A1 and A2 operating in parallel with the utility grid. Test 7.14 tested a phase-to-phase overload fault condition in Zone 4 with Gen-sets A1 and A2 operating in parallel with the utility grid. Test 7.15 tested a phase-to-phase overload fault condition in Zone 2 with Gen-sets A1 and B1 operating in-parallel with the utility grid. Test 7.16 tested a phase-to-phase overload fault condition in Zone 5 with Gen-sets A1 and B1 operating in parallel with the utility grid.

Table 2 summarizes the test performance goals and results from each of these tests.

Test Description	Performance Goal	Results
7.1. Validate zone 4 circuit breaker settings, utility connected	Initially test a three-phase balanced fault condition in Zone 4 to verify I^2t protection. Then test a single line-to-ground fault condition in Zone 4 to verify zero-sequence, negative-sequence or residual over-current protection.	Relay 4 detected an I^2t protection event and opened circuit breaker CB41 during the three-phase balanced fault. All other breakers remained closed. Relay 2 detected a ground over-current during the single line-to-ground fault and opened the static switch. All other breakers remained closed.
7.2. Validate zone 3 circuit breaker settings, utility connected	Initially test a three-phase balanced fault condition in Zone 3 to verify I^2t protection. Then test a single line-to-ground fault condition in Zone 3 to verify zero-sequence, negative-sequence or residual over-current protection.	Relay 3 detected an I^2t protection event and opened circuit breaker CB31 during the three-phase balanced fault. All other breakers remained closed. Relay 2 detected a ground over-current during the single line-to-ground fault and opened the static switch. All other breakers remained closed.
7.3. Validate zone 5 circuit breaker settings, utility connected	Initially test a three-phase balanced fault condition in Zone 5 to verify I^2t protection. Then test a single line-to-ground fault condition in Zone 5 to verify zero-sequence, negative-sequence or residual over-current protection	Relay 5 detected an I^2t protection event and opened circuit breaker 5 during the three-phase balanced fault. All other breakers remained closed. Relay 5 detected a negative-sequence over-current during the single line-to-ground fault and opened circuit breaker CB51. All other breakers remained closed.
7.4. Zone 4 three-phase un-grounded fault, gen-sets (A1+A2), utility connected	Test a three-phase balanced fault condition in Zone 4 with Gen-sets A1 and A2 operating in-parallel with the utility grid to verify I^2t protection, plus confirm a reverse power event after the Zone breaker "opens".	Relay 4 detected an I^2t protection and opened circuit breaker CB41. The static switch opened 30 seconds later due to a reverse power event.
7.5. Zone 3 A-phase line-to-ground fault, gen-set A1, utility connected	Test a single line-to-ground fault condition in Zone 3 with Gen-sets A1 operating in-parallel with the utility grid to verify zero-sequence, negative-sequence or residual over-current protection.	Relay 2 detected a ground over-current and opened the static switch within a cycle. Relay 3 opened circuit breaker CB31 0.15 seconds after the static switch when it detected a ground over-current
7.6. Zone 3 A-phase line-to-ground fault,	Test a single line-to-ground fault condition in Zone 3 with Gen-sets A1 and A2 operating in-	Relay 2 detected a ground over-current and opened the static switch in 0.02 seconds. Relay 4 opened circuit breaker CB41 0.07 seconds

gen-sets (A1+A2), utility connected	parallel with the utility grid to verify zero-sequence, negative-sequence or residual over-current protection	after the static switch when it detected a neutral over-current. Relay 3 opened circuit breaker CB31 0.04 seconds after circuit breaker CB41 when it detected a ground over-current.
7.7. Zone 5 B-phase line-to-ground fault, gen-set B1, utility connected	Test a single line-to-ground fault condition in Zone 5 with Gen-sets B1 operating in-parallel with the utility grid to verify zero-sequence, negative-sequence or residual over-current protection	Relay 5 opened circuit breaker CB51 in 0.07 seconds when it detected a ground over-current. The static switch opened 0.03 seconds after circuit breaker CB51 when it detected a negative sequence over-current.
7.8. Zone 5 B-phase line-to-ground fault, gen-sets (A1+B1), utility connected	Test a single line-to-ground fault condition in Zone 5 with Gen-sets A1 and B1 operating in-parallel with the utility grid to verify zero-sequence, negative-sequence or residual over-current protection. This test is similar to the prior test, but evaluates the resultant impact of two Gen-sets operating during a fault condition	Relay 5 opened circuit breaker CB51 in 0.06 seconds when it detected a ground over-current. All other breakers remained closed.
7.9. Zone 4 B-phase line-to-ground fault, gen-sets (A1+A2), utility connected	Test a single line-to-ground fault condition in Zone 4 with Gen-sets A1 and A2 operating in-parallel with the utility grid to verify zero-sequence, negative-sequence or residual over-current protection.	Relay 2 detected a ground over-current and opened the static switch within a cycle. Relay 4 opened circuit breaker 4 0.058 seconds after the static switch when it detected a ground over-current.
7.10. Zone 2 C-phase line-to-ground fault, gen-sets (A1+B1), utility connected	Test a single line-to-ground fault condition in Zone 2 with Gen-sets A1 and B1 operating in-parallel with the utility grid to verify zero-sequence, negative-sequence or residual over-current protection.	Relay 2 detected a ground over-current and opened the static switch within a cycle. Relay 3 opened circuit breaker CB31 0.17 seconds after the static switch when it detected a ground over-current. Relay 5 opened circuit breaker CB51 due to an under-voltage condition.
7.11. Zone 6 C-phase line-to-ground fault, gen-set A1, utility connected	Test a single line-to-ground fault condition in Zone 6 with Gen-set A1 operating in-parallel with the utility grid to verify I^2t protection.	Relay 2 detected a neutral over-current and opened the static switch in 0.07 seconds. Circuit breaker CB13 tripped on an I^2t protection event.

7.12. Zone 6 C-phase line-to-ground fault, gen-sets (A1+B1), utility connected	Test a single line-to-ground fault condition in Zone 6 with Gen-sets A1 and B1 operating in-parallel with the utility grid to verify I^2t protection. This test is similar to the prior test, but evaluates the resultant impact of two Gen-sets operating during a fault condition.	Relay 2 detected a neutral over-current and opened the static switch in 0.07 seconds. Circuit breaker CB13 tripped on an I^2t protection event.
7.13. Zone 3 A-to-B phase fault, gen-sets (A1+A2), utility connected	Test a phase-to-phase fault condition in Zone 3 with Gen-sets A1 and A2 operating in-parallel with the utility grid to verify negative-sequence, I^2t protection or residual over-current protection.	Relay 2 detected a negative sequence over-current and opened the static switch in 0.028 seconds. All other breakers remained online.
7.14. Zone 4 A-to-B phase fault, gen-sets (A1+A2), utility	Test a phase-to-phase fault condition in Zone 4 with Gen-sets A1 and A2 operating in-parallel with the utility grid to verify negative-sequence, I^2t protection or residual over-current protection.	Relay 2 detected a negative sequence over-current and opened the static switch in 0.078 seconds. Relay 4 opened circuit breaker CB41 after the static switch when it detected a negative sequence over-current.
7.15. Zone 2 A-to-B phase fault, gen-sets (A1+B1), utility connected	Test a phase-to-phase fault condition in Zone 2 with Gen-sets A1 and B1 operating in-parallel with the utility grid to verify negative-sequence, I^2t protection or residual over-current protection.	There was not enough current produced by the fault, therefore, all breakers remained closed during the test.
7.16. Zone 5 A-to-B phase fault, gen-sets (A1+B1), utility connected	Test a phase-to-phase fault condition in Zone 5 with Gen-sets A1 and B1 operating in-parallel with the utility grid to verify negative-sequence, I^2t protection or residual over-current protection.	Relay 5 detected a negative sequence over-current and opened circuit breaker in 0.075 seconds. Relay 2 opened the static switch 0.016 seconds after circuit breaker CB51 when it detected a negative sequence over-current.

Table 2. Internal Protection Testing Summary

The third set of tests (Section 8 of the test plan) was designed to ensure that the Gen-set inverter controls were working as designed. This includes unit control, zone control, and mixed power controls, in conjunction with limit controls and synchronized closing of the static switch. These tests were based on replicating tests that had previously been conducted by Tecogen and Youtility during the factory acceptance testing of the standalone inverters, and the engine coupled inverters. The performance goal was to observe smooth transitions of the Gen-sets response to different step conditions (i.e., static switch “OPEN”/ “CLOSE” and load steps). Thirteen separate tests were conducted.

Test 8.1 verified smooth transitions in Gen-set A1 when different step conditions of load are applied in Load Bank 3 with voltage set points ranging from +5% to -5%. The same test was repeated for Gen-set A2 and Load Bank 4 and Gen-set B1 and Load Bank 5.

Test 8.2 verified smooth transitions of Gen-sets A1 and A2 response to different step conditions which drive Gen-set A1 to a lower limit of zero kW.

Test 8.3 verified smooth transitions of Gen-sets A1 and A2 response to different step conditions which drive Gen-set A2 to an upper limit of 60kW.

Test 8.4 verified smooth transitions of Gen-sets A1 and A2 response to different step conditions with an un-balanced load in Zone 3.

Test 8.5 verified smooth transitions of Gen-sets, A1 in Zone operation mode and A2 in Unit operation mode. During a load step change in Load Bank 3, Gen-set A1 was driven to an upper limit of 60kW.

Test 8.6 verified smooth transitions of Gen-sets, A1 in zone operation mode and Gen-set A2 in Unit operation mode. During a load step change in Load Bank 4, Gen-set A1 is driven to its maximum which causes an automatic reset of the zone set points.

Test 8.7 verified smooth transitions of Gen-sets, A1 in Zone operation mode and A2 in Unit operation mode, with a change of zone power in Feeder A.

Test 8.8 verified smooth transition of Gen-sets, A1 in Zone operation mode and A2 in Unit operation mode, with a static switch operation and a change of zone power in Zone 3 when islanded.

Test 8.9 verified smooth transition of Gen-sets, A1 in Zone operation mode and A2 in Unit operation mode, with a static switch operation and a change of zone power in Zone 3 when islanded. Gen-set A1 was driven to its maximum which caused an automatic reset of both Gen-sets set-points.

Test 8.10 verified smooth transitions of Gen-sets, A1 and B1 in Zone operation mode, with a static switch operation and a change of zone power in Zones 3 and 5 when islanded.

Test 8.11 verified smooth transitions of Gen-sets, A1 and B1 in Zone operation mode, with a static switch operation and a change of zone power in Zones 3 and 5 when islanded. When

islanded, Gen-set A1 and B1 set-points were reset based on the remaining load in the islanded system.

Test 8.12 tested the manual procedure used to black-start the CERTS Micro-grid Test Bed in the event of a lengthy utility outage occurs with the Gen-sets off-line.

Test 8.13 was designed to determine the black-start capacity by increasing the amount of load on the CERTS Microgrid Test Bed from a black-out condition without generation or protection trips.

Table 3 summarizes the test performance goals and results from each of these tests

Test Description	Performance Goal	Results
8.1. Initial voltage regulation test – single zone, islanded with gen-set A1	Verify smooth transitions of Gen-set A1 response to different step conditions of load in Load Bank 3 with voltage set point changes ranging from +5% to -5%. Repeat tests with Gen-set A2 in Load Bank 4, and then Gen-set B1 in Load Bank 5	All Gen-sets had smooth transitions through each load step and voltage change.
8.2. Open static switch test, check P = 0 limit, gen-set A1	Verify smooth transitions of Gen-sets A1 and A2 response to different step conditions (i.e., static switch “OPEN”/ “CLOSE”) with the unit power limit of Gen-set A1 equal to zero	Gen-sets had smooth transition from grid connected to island mode and vice versa. All Gen-sets responded as predicted.
8.3. Open static switch test, check P = 60kW limit, gen-set A2	Verify smooth transitions of Gen-sets A1 and A2 response to different step conditions (i.e., static switch “OPEN”/ “CLOSE”) with the unit power limit of Gen-set A2 equal to 60kW	Gen-sets had smooth transition from grid connected to island mode and vice versa. All Gen-sets responded as predicted.
8.4. Test island operation, unbalanced load	Verify smooth transitions of Gen-sets A1 and A2 response to different step conditions (i.e., static switch “OPEN”/ “CLOSE”) with an un-balanced load condition in Zone 3	Gen-sets had smooth transition from grid connected to island mode and vice versa. All Gen-sets responded as predicted.
8.5. Mixed mode operation test – Zone 3 and 4, gen-set A1 to 60kW maximum	Verify smooth transitions of Gen-sets, A1 in Zone operation mode with a 60kW limit and A2 in Unit operation mode, during a load step change in Load Bank 3	Gen-set had smooth transition from grid connected to island mode and vice versa. Gen-sets responded as predicted.
8.6. Mixed mode operation test – Zones 3 and 4, automatic reset of zone level set-point	Verify smooth transitions of Gen-sets, A1 in Zone operation mode with an automatic reset of the set point and A2 in Unit operation mode, during a load step change in Load Bank 4	Gen-sets had smooth transition from grid connected to island mode and vice versa. All Gen-sets responded as predicted.
8.7. Mixed mode operation test –	Verify smooth transitions of Gen-sets, A1 in Zone	Gen-sets had smooth transition from

Zones 3 and 4, zone power change	operation mode and A2 in Unit operation mode, with a change of zone power in Feeder A	grid connected to island mode and vice versa. All Gen-sets responded as predicted.
8.8. Mixed mode operation test – Zones 3 and 4 , zone power change when islanded	Verify smooth transitions of Gen-sets, A1 in Zone operation mode and A2 in Unit operation mode, with a static switch operation and a change of zone power in Zone 3 when islanded	Gen-sets had smooth transition from grid connected to island mode and vice versa. All Gen-sets responded as predicted.
8.9. Mixed mode operation test – Zones 3 and 4, when islanded, automatic reset of zone level set-point, both gen-sets P = 60kW Maximum	Verify smooth transitions of Gen-sets, A1 in Zone operation mode with automatic reset of set point and A2 in Unit operation mode, with a static switch operation and a change of zone power in Zone 3 when islanded	Gen-sets had smooth transition from grid connected to island mode and vice versa. All Gen-sets responded as predicted.
8.10. Two sources in zone control - separate zones, when islanded, automatic reset of zone level set-point, new zones sum equal zero	Verify smooth transitions of Gen-sets, A1 and B1 in Zone operation mode, with a static switch operation and a change of zone power in Zones 3 and 5 when islanded	Gen-sets had smooth transition from grid connected to island mode and vice versa. All Gen-sets responded as predicted.
8.11. Two sources in zone control - separate zones, when islanded, automatic reset of zone level set-points	Verify smooth transitions of Gen-sets, A1 and B1 in Zone operation mode and both having automatic reset of set points, with a static switch operation and a change of zone power in Zones 3 and 5 when islanded	Gen-sets had smooth transition from grid connected to island mode and vice versa. All Gen-sets responded as predicted.
8.12. Test generator black-start	<p>Bring up the Microgrid Test Bed from a black-out condition without generation or protection trips.</p> <p>Measurement – Record the transition of the Gen-set meters as they are started and brought on-line and as load banks are switched on-line. Note, the transition time between all events outage occurs with the Gen-sets off-line</p> <p>This test checks the manual procedure used to black-start the Microgrid Test Bed in the event of a lengthy utility</p>	Gen-sets had smooth transitions and met the load demand.

8.13. Test/establish generator black-start capacity	Determine the Black-start capacity of the microgrid by increasing the amount of load on the Microgrid Test Bed from a black-out condition without generation or protection trips	Total capacity was not determined because the Gen-set stayed online during each test supplying the load demand even for the 70kW + j30kVAr load. This test proved that the Gen-sets are more robust for blackstart then previously predicted.
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Table 3. Reduced System Testing Summary

The fourth set of tests (Section 9 of the test plan) demonstrated the flexibility of the microgrid both grid connected and islanded for different loads, power flows and impact on the utility. The tests included the “weak grid” inductors (i.e., L11) in the circuit. Three sets of tests were conducted.

Tests 9.1 – 9.3 verified and documented power flow and microgrid frequency changes when transitioning from utility connected to an islanded mode of operation. In each test, 9.1 – 9.3, a series of tests were performed that vary in the amount of load that is applied to the microgrid in a weak grid scenario along with the power settings of each Gen-set. The difference between each test is the type of control mode that the Gen-sets are in. In Test 9.1, all the Gen-sets were set for unit control mode and then the next test, 9.2, all the Gen-sets were set for zone control mode. Test 9.3 mixed the unit and zone control modes of the Gen-sets during each test.

Table 4 summarizes the test performance goals and results from each of these tests

Test Description	Performance Goal	Results
9.1. Unit control mode, weak grid	Verify and document power flow and Microgrid frequency changes when transitioning from utility connected to an islanded mode of operation. During each sequence of tests , maintain a weak grid connection with L11 in the circuit and the static switch “Closed”; all zone and load bank circuit breakers “Closed”; Gen-sets A1, A2 and B1 set for Unit (injection power) control mode; and all load banks initially set at zero	Voltage and frequency remained stable during grid connected to island mode and vice versa for all four tests. Control of Power was as expected from Gen-sets to load demand.
9.2. Zone control mode, weak grid	Verify and document power flow and Microgrid frequency changes when transitioning from utility connected to an islanded mode of operation.	Voltage and frequency remained stable during grid connected to island mode and vice versa for all four tests. Control of Power was as expected from Gen-sets to load demand.
9.3. Mixed zone and unit control modes, weak grid	Verify and document power flow and Microgrid frequency changes when transitioning from utility connected to an islanded mode of operation.	Voltage and frequency remained stable during grid connected to island mode and vice versa for all four tests. Control of Power was as expected from Gen-sets to load demand.

Table 4. Power Flow Control Testing Summary

The fifth and final set of testing (Section 10 of the test plan) began to explore the operation limits of the microgrid (i.e., power quality, protection and inverter limits). Two primary sets of tests were conducted under weak grid conditions; the first involved induction motor starting loads under balanced and unbalanced load conditions; the second involved only unbalanced loads.

Motor start tests conducted in Test 10.2 had balanced loads at a 0.9 power factor under weak grid conditions. These tests verified and documented power flow, microgrid frequency changes, and protection design with different Gen-set settings during motor starts when utility connected and then again during islanded mode of operation. Test 10.3 was similar to Test 10.2, except that the loads were unbalanced with a 0.9 power factor.

In Test 10.4 verified and documented power flow, microgrid frequency changes, and protection design with different Gen-set settings during changes of unbalanced load in load banks.

Table 5 summarizes the test performance goals and results from each of these tests.

Test Description	Performance Goal	Results
10.2. Motor Start Tests, Weak Grid, Balanced Load	Verify and document power flow, Micro-grid frequency changes and protection design with different Gen-set settings during motor starts when utility connected and island mode of operation.	CERTS Microgrid remained electrically stable during the 10 Hp induction motor start in Zone 3 while utility connected and islanded mode for all six test.
10.3. Motor Start Tests, Weak Grid, Unbalanced Load	Verify and document power flow, Micro-grid frequency changes and protection design with different Gen-set settings during motor starts when utility connected and island mode of operation.	CERTS Microgrid remained electrically stable during the 10 Hp induction motor start in Zone 3 while utility connected and islanded mode for all six test.
10.4. Unbalanced Load Tests, Weak Grid	Verify and document power flow, Micro-grid frequency changes and protection design with different Gen-set settings during changes of unbalanced load in Load Banks while utility connected and in islanded mode of operation.	Static switch opened on a reverse power trip while utility connected in Tests 10.4.12 and 10.4.14 when Load Banks 3 and 6 A-phase was reduced by 50%. CERTS Microgrid remained electrically stable when the A-phase in the load demands equaled 0kW and in island mode of operation. The static switched opened on a reverse power trip for all three tests when the microgrid was reconnected to the utility grid. Once the static switch opened, the CERTS microgrid remained electrically stable. All test results performed as predicted.

Table 5. Difficult Load Testing Summary

The testing fully confirmed earlier research that had been conducted initially through analytical simulations, then through laboratory emulations, and finally through factory acceptance testing of individual microgrid components. The islanding and resynchronization method met all IEEE 1547 and power quality requirements. The electrical protection system was able to distinguish between normal and faulted operation. The controls were found to be robust under all conditions, including difficult motor starts.

Test bed results were then presented and discussed jointly with and then reviewed individually by members of the TAC. The reviews were uniformly positive:

“Concepts are elegant, yet simple. Simple translates to more affordable.”

“Demonstration that static switch can comply with 1547, with non-compliant generation behind it, is a major accomplishment. The team has confirmed that a static switch is very fast. It is recognized that ground fault testing on the utility side of the static switch is still missing from this aspect of 1547 compliance.”

“Inverter controls are impressive.”

“Test plan was well laid-out. A wide range of concerns that were identified have now been successfully addressed. In particular, motor starting was a challenging test and the results are very encouraging. Should be a major contribution to the literature.”

“The test bed platform should be used for future research.”

A summary of the TAC meeting at which test bed results were reviewed as well as the additional written comments received from the TAC are contained in Appendix O. Technical Advisory Committee Meeting Summary and Review Comments.

In addition, AEP has prepared a standalone technical assessment and recommendations:

“The major objective of plug and play gen-sets has been proven to work very well and is seen as a major stepping stone toward increasing the commercial adoption of microgrids. The keystone of this plug and play approach is the CERTS frequency versus power and voltage versus VAR algorithms which have proven to be robust in the control of multiple voltage source inverters on a common bus. The specific advantages offered by this approach are expected to include: improved operation, more manageable equipment requirements, all at lower total system costs compared to a traditional custom-designed distributed generation power system involving multiple prime movers.

In addition, the concept of placing generation, which is non-compliant with IEEE Standard 1547, beyond a static switch, which is compliant, was tested and proven to be successful. This is expected to be another effective tool in reducing the cost of a

traditional custom-designed, distributed generation power system involving multiple prime movers, while still maintaining safe interconnection with a utility system.

It is recognized that the tests conducted by AEP represent the first full-scale tests of the CERTS Microgrid Concept. AEP looks forward to participation in future research and testing to advance this Concept. Toward this end, we recommend focus on the following areas:

1. Demonstrate the ability of power electronic inverters to adjust fault contribution from the gen-sets.
2. Re-examine and potentially re-tune the anti-islanding philosophy governing operation of the static switch, in light of expected unbalanced voltages presented by utility distribution systems to the microgrid.
3. Develop and test means for minimizing VAR flows by using the Energy Manager to direct voltage set-point changes to the gen-sets based on actual voltages on the utility distribution system.
4. Continue testing to explore performance of the CERTS Microgrid in supporting difficult loads.
5. Confirm the adequacy or revise the management of the static switch when the utility closes into a dead bus.
6. Examine enhanced functionalities for the Energy Manager to address customer and utility needs, such as power factor correction, fault and error handling, energy efficiency, and price- or reliability-driven demand management.
7. Examine system impacts for scenarios involving significant deployment of microgrids.”

3.3.3. Microgrid Protective Relaying Design

Traditionally, power flow in the existing electrical infrastructure flows from the power plant through transmission and possibly distribution lines to the load that is demanding power. Protection schemes were based on this concept, which allowed for uni-directional over-current protection devices to be installed. Uni-directional over-current protection devices sense when there is a fault on the electrical system by opening up when the current exceeds a certain value in a certain direction.

Uni-directional over-current protection schemes are not feasible within microgrids, because of microgrids’ reverse power-flow capability; if current is flowing in the opposite direction (i.e., from the microsources toward the point of common coupling (PCC)), it will not trip the over-current device when a fault occurs. A microgrid can use bi-directional over-current protection devices when the microgrid is connected to the utility but not while the microgrid is islanded. During islanded operation, the microgrid fault current magnitudes are less significant than

when the microgrid is connected to the utility, so uni-directional and bi-directional detection may not detect the fault current preventing the protection device from operating.

The team developed a protection scheme that uses sequence components to detect low-fault currents in utility-connected and islanded operation. Sequence components take a balanced or unbalanced voltage or current and break it up into three separate components: positive, negative, and zero sequence. Adding these three components together gives the magnitude and phase angle of balanced and unbalanced currents and voltages. A single line-to-ground fault produces a zero sequence current, providing a trip signal for the zone with the fault that does not depend on the direction of the current and magnitude as is the case with traditional over-current protection devices. A line-to-line fault produces a negative sequence current that signals the zone with the fault to trip. This protection scheme allows for plug-and-play without changing the existing over-current devices on the electrical system.

The technical report on the microgrid protective relaying design is contained in Appendix O. Microgrid Fault Protection Based on Symmetrical and Differential Current Components.

3.4. Field Demonstration Planning (Task 2.4)

The goal of task 2.4 was to identify and engage one or more partners for a field demonstration of the CERTS Microgrid concept. While a field demonstration was not included in the project plan for this project, it was important to engage potential partners prior to and during the laboratory test bed phase so that partner-specific technical or operational issues could be addressed in the laboratory test bed prior to conducting a field demonstration.

The identification of potential field demonstration partners took place through a variety of means. Central to most of them was outreach conducted through a variety of presentations and publications.

Presentations

R.H. Lasseter, "Advanced Distribution using DER," Rethinking T&D Architecture for DER, 24 April 2008, T&D Panel, Chicago

R.H. Lasseter, "DER and Microgrids," IEEE Distinguish Lecturer, IEEE PES St. Louis chapter, 6 November 2007

R.H. Lasseter, "Microgrids and Distributed Generation," ASCE Journal Energy Engineering, Volume 133, Number 3, September 2007.

H. Nikkhajoei and R.H. Lasseter, "Microgrid Protection," IEEE Panel: Microgrid Research and Field Testing, IEEE PES General Meeting, 24-28 June 2007, Tampa, FL

R.H. Lasseter, "Extended Microgrid Using (DER) Distributed Energy Resources," IEEE Panel: Sustainable Energy, IEEE PES General Meeting, 24-28 June 2007, Tampa, FL

R.H. Lasseter, "CERTS Microgrid," Panel on Microgrids Systems, International Conference on System of Systems Engineering, April 16-18, 2007 San Antonio

R.H. Lasseter, "CERTS Microgrid," ERDC/CERL_RDCOM, Army Engineers, 18 January 2007, Champaign, Ill.

R.H. Lasseter, "Microgrids on Distribution Scale," Panel, Army Installation Energy Security & Independence Conference, Greensboro, N.C., 12-13 December 2006

R.H. Lasseter. "Methods for Controlling Multiple Independent Generators in an Intentional Island (Microgrids)," Minnesota Power 11/8/06

R.H. Lasseter. "Distributed Energy Resources and Microgrids," IEEE Distinguish Lecturer, IEEE Cuernavaca, Mexico, 2 July 2006.

R.H. Lasseter. "Directions In Microgrid research", PSerc Lecture, 6 June 2006, Madison, Wi

R.H. Lasseter." Autonomous Control", 2006 PES General Meeting, 22 June 2006, Montréal, Québec Canada

R.H. Lasseter. "Microgrids and Protection", CERTS IAB Meeting, 27 June 2006, Cleveland, Ohio

R.H. Lasseter. "Enhanced Microgrid", Microgrid Road Map. 18 May 2006, Office of Electric Energy, Washington, DC

R.H. Lasseter. "Dynamics Distribution", IEEE T&D Meeting, Panel on Future of Distribution, Dallas, 20 May 2006 "Enhanced Business Case for CERTS Microgrid", Peer Review Meeting for the Department of Energy's , Electric Distribution R&D Program, 26 May 2006, San Ramon Ca

R.H. Lasseter. "The Role of Distributed Energy Resources in Future Electric Power Systems", Energy System Seminar, 27 March 2006, Madison, Wi

R.H. Lasseter. "DER based Distribution", DOE Energy Workshop, Panel, January 31 to February 1 2006, Tallahassee, Fl

R.H. Lasseter. "Microgrid Test Plan", CERTS IAB Meeting, 6 October 2005, Cleveland, Ohio

R.H. Lasseter. "CERTS Microgrid", International Microgrid Workshop, Panel Speaker, 17 June 2005, University of California-Berkeley, Berkeley, California

R.H. Lasseter. "CERTS Microgrid", California Energy Commission R&D Forum, 4 May 2005, Sacramento, Ca

R.H. Lasseter. *"Microgrid: A Conceptual Solution,"* Wisconsin Distributed Resources Collaborative, September 16, 2004

R.H. Lasseter. "CERTS Microgrid," CEC Technical Advisory Committee Meeting, July 19, 2004

R.H. Lasseter. *"Where are Microgrids Going?,"* Distributed Resources Workshop, CEA, May 9-11, 2004 Calgary

R.H. Lasseter. *"Microgrids: What's Next,"* PSerc Industrial Advisory Board, May 20-21, 2004

Publications

Klapp, D., H.T. Vollkommer. *Application of an Intelligent Static Switch to the Point of Common Coupling to Satisfy IEEE 1547 Compliance*. Panel: Microgrid Research and Field Testing IEEE PES General Meeting, 24-28 June 2007, Tampa, FL. 4 pages.

Lasseter, R.H., P. Piagi. 2006. *Control and Design of Microgrid Components*. January. 257 pages. <http://www.pserc.org/ecow/getpublicatio/reports/2006report>

Lasseter, R. *Dynamic Distribution using (DER) Distributed Energy Resources*. 2006. IEEE PES T & D Meeting, Dallas, May. 3 pages.

Lasseter, R.H. 2007. "Microgrids and Distributed Generation." *Journal of Energy Engineering*, Volume 133, Issue3, ASCE, Sept. 7 pages.

Lasseter, R.H. 2007. "CERTS Microgrid." International Conference on System of Systems Engineering , April 16-18. 6 pages.

Nichols, D.K., J. Stevens, R.H. Lasseter, J.H. Eto, H.T. Vollkommer. 2006 *Validation of the CERTS Microgrid Concept: The CEC/CERTS Microgrid Testbed*. Power Engineering Society General Meeting, IEEE. 3 pages.

Nikkhajoie, H., R. H. Lasseter. 2007. *Microgrid Protection*. IEEE PES General Meeting, 24-28, Tampa, FL. June. 6 pages.

Nikkhajoie, H., R. H. Lasseter. 2006. *Microgrid Fault Protection Based on Symmetrical and Differential Current Components*. December. 72 pages. (Power Systems Engineering Research Center (PSERC) website)

Panora, R.A., J.B. Gehret Jr., P. Piagi. 2007. *Design and Testing of an Inverter-Based Combined Heat and Power Module for Special Application in a Microgrid*. Panel: Microgrid Research and Field Testing IEEE PES General Meeting, June 24-28, Tampa FL. 7 pages.

Stevens, J., H. Vollkommer, D.Klapp. CERTS Microgrid System Tests. Power Engineering Society General Meeting, June 24-28. 4 pages.

In addition, the CERTS Microgrid concepts have appeared in Distributed Energy Journal, May/June 2008, which can be found at http://www.distributedenergy.com/de_0805_micro.html.

Through this outreach, members of the CERTS team met with a wide variety of potential field demonstrations partners during the course of the project. A separate Energy Commission contract to Navigant Consulting further augmented efforts to develop field demonstrations involving the CERTS Microgrid concept.

At the time of the preparation of this report, the status of discussions with potential partners for field demonstrations involving the CERTS Microgrid Concept is as follows:

Tecogen, a partner in the CERTS Microgrid Test Bed project, is currently conducting a research project for the New York State Energy Research and Development Authority to demonstrate aspects of the CERTS Microgrid Concept at a school in upstate New York.

The Energy Commission PIER program is considering funding for two demonstrations involving aspects of the CERTS Microgrid Concept. Chevron Energy Solutions is proposed to lead a demonstration, which would involve battery storage, renewable energy, and engine generators at a correctional facility in Northern California. Sacramento Municipal Utilities District (SMUD) is proposed to lead a demonstration that would involve engine generators at SMUD corporate headquarters.

Two additional demonstrations involving aspects of the CERTS Microgrid Concept have been submitted in response to a competitive solicitation from the U.S. Department of Energy (DOE). The identities of the firms leading these proposals are being withheld pending the announcement of solicitation awardees by DOE.

In addition, active discussions are also under way for additional field demonstrations, involving the U.S. Army Corp of Engineers/Construction Research Laboratory and with Cummins Engines.

4.0 Conclusions and Recommendations

This section describes the conclusions drawn from the successful demonstration of the CERTS Microgrid concept at a full-scale test bed operated by AEP and lists recommendations for future work.

4.1. Conclusions

The objective of the CERTS Microgrid Laboratory Test Bed Demonstration project was to demonstrate three advanced techniques comprising the CERTS Microgrid concept at a full-scale test bed operated by AEP.

The advance techniques, which included: 1) a method for effecting automatic and seamless transitions between grid-connected and islanded modes of operation; 2) an approach to electrical protection within the microgrid that does not depend on high fault currents; and 3) a new method for microgrid control that achieves voltage and frequency stability under islanded conditions without requiring high-speed communications, were demonstrated through a carefully orchestrated sequence of five sets of tests by AEP.

The first set of tests examined the operation of the static switch to determine that it and its digital signal processing (DSP) control operated as designed. The second set of tests examined a preliminary set of fault (i.e., overload simulating a fault) condition tests to ensure protection and safety of the test bed, prior to performing other planned tests. The third set of tests was designed to ensure that the Gen-set inverter controls were working as designed. The fourth set of tests demonstrated the flexibility of the microgrid both grid connected and islanded for different loads, power flows and impact on the utility. The fifth and final set of testing began to explore the operation limits of the microgrid (i.e., power quality, protection and inverter limits) with motor starting loads.

The testing fully confirmed earlier research that had been conducted initially through analytical simulations, then through laboratory emulations, and finally through factory acceptance testing of individual microgrid components. The islanding and resynchronization method met all IEEE 1547 and power quality requirements. The electrical protection system was able to distinguish between normal and faulted operation. The controls were found to be robust under all conditions.

4.2. Recommendations

The next logical phase for RD&D on the CERTS Microgrid Concept is to build from the base established by the currently operational CERTS Microgrid to prioritize, develop, and then demonstrate needed additional technology enhancements required to optimize the microgrid from the explicit perspective of enhancing the business case for microgrids. That is, having demonstrated the technical feasibility of microgrid functions, RD&D optimization efforts are now needed to accelerate commercial deployment. The should pay special attention to the economic drivers, such as economic dispatch responsive to pricing signals and demand management programs, customer willingness to pay premiums for increased power reliability and quality, etc.

In order to enhance the business case for microgrids, the cost and functionalities of the CERTS Microgrid need to be compared directly against traditional solutions for a) CHP including the heat distribution systems and system reliability, and b) power quality, including multiple feeders and/or UPS systems. That is, enhancing the business case for microgrids involves, first, identifying the cost and performance targets of the traditional approaches for providing the values offered by a microgrid and then, second, prioritizing development and testing of CERTS Microgrid technology enhancements to beat these targets. Some promising areas to consider include: 1) lowering the costs of providing protection among microsources and loads; 2) determining the optimal amount of storage required on the DC bus; 3) the best size, technology, and control strategy (or strategies) for integration of AC storage; and 4) inclusion of non-inverter-based prime-movers along side of inverter-based prime-movers within a microgrid.

4.3. Benefits to California

DER – small power generators typically located at sites where the energy (both electric and thermal) they generate is used – are a promising option to meet growing customer needs for economic and reliable electric power (the DER portfolio also includes energy storage, and load control). Organizing all of these resources into microgrids is a promising way to capture smaller DER's significant potential to meet customers' and utilities' needs.

A key feature of a microgrid is its ability, during a utility grid disturbance, to separate and isolate itself from the utility seamlessly with no disruption to the loads within the microgrid (including no reduction in power quality). Then, when the utility grid returns to normal, the microgrid automatically resynchronizes and reconnects itself to the grid, in an equally seamless fashion.

The CERTS Microgrid concept seeks to provide this technically challenging functionality without extensive (i.e., expensive) custom engineering. In addition, the design of the CERTS Microgrid also provides high system reliability and great flexibility in the placement of distributed generation within the microgrid. The CERTS Microgrid is intended to offer these functionalities at much lower costs than traditional approaches by incorporating *peer-to-peer* and *plug-and-play* concepts for each component within the microgrid.

In so doing, the CERTS Microgrid concept will help improve the quality of life in California by bringing environmentally safe, affordable, and reliable energy services and products to the marketplace.

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6.0 Glossary

Acronym	Definition
AC	alternating current
AEP	American Electric Power
CERTS	Consortium for Electric Reliability Technology Solutions
CHP	combined heat and power
DC	direct current
DER	distributed energy resources
DOE	Department of Energy
EMS	energy management system (a control system that optimizes operation of the Microgrid to economically meet electricity and heat loads)
EPRI	Electric Power Research Institute
Energy Commission	California Energy Commission
IEEE	Institute of Electrical and Electronics Engineers
LBNL	Lawrence Berkeley National Laboratory
NPS	Northern Power Systems
NREL	National Renewable Energy Laboratory
PCC	point of common coupling
PIER	Public Interest Energy Research
PSERC	Power Systems Engineering Research Center
RD&D	research, development, and demonstration
SCE	Southern California Edison
SMUD	Sacramento Municipal Utilities District
SNL	Sandia National Laboratories
Static Switch	Separation device used to interconnect microgrid with distribution system
TAC	Technical Advisory Committee
UW	University of Wisconsin

Appendices

Appendices are available as separate documents

Appendix A. Test Bed Design Schematics

Appendix B. CERTS Microgrid Test Plan

Appendix C. Youtility Factory Test Plan Final Test Results

Appendix D. Tecogen 60kW Inverter-Based CHP Modules: Factory Testing

Appendix E. Tecogen CHP Modules Commissioning Report

Appendix F. CERTS Test Bed CERTEQUIP-V06-002, CERTS Switch, Low Power Factory Acceptance Test Report

Appendix G. Summary of CERTS Microgrid Static Switch Power Quality Tests at AEP Dolan, CERTS Microgrid Static Switch Testing

Appendix H. CERTS Test Bed Design and Commissioning: Lessons Learned Summary

Appendix I. Test Plan Section 6.0 Microgrid Test Bed System Checkout (Static Switch)

Appendix J. Test Plan Section 7.0 Validate Protection Settings and Initial Fault Testing

Appendix K. Test Plan Section 8.0 Reduced System Tests

Appendix L. Test Plan Section 9.0 Power Flow Control Tests

Appendix M. Test Plan Section 10.0 Difficult Loads

Appendix N. Test Log

Appendix O. Technical Advisory Committee Meeting Summary and Review Comments

Appendix P. Microgrid Fault Protection Based on Symmetrical and Differential Current Components